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DEFINITION OF DAMAGE STATES FOR DEVELOPING ANALYTICAL TSUNAMI FRAGILITY FUNCTIONS

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Abstract: *In a probabilistic risk-assessment framework, tsunami fragility functions are fundamental for assessing damage and vulnerability of buildings due to the action of tsunami waves. Several sets of empirical fragility functions were built after major tsunami events, such as Sumatra 2004, Tohoku 2011 or Chile 2015. However, just few studies approached at the definition of analytical fragility functions for estimating the effects of tsunami waves on coastal residential areas. The crucial aspect in deriving analytical fragility functions for reinforced concrete (RC) buildings is the definition of damage limit states associated to mechanical models for both structural and non-structural components. Literature models available for developing analytical fragility functions commonly neglect the damage to non-structural components. However, the post-earthquake reconstruction experience in L'Aquila attested that the damage to non-structural components strongly affected the economic losses. Thus, in this work analytical damage limit states for both structural and non-structural components were defined based on damage observed for RC buildings after major tsunami events. Then, mechanical models were proposed for predicting the proposed damage for non-structural and structural members.*

Introduction

Due to the widespread number of destroying tsunami events all over the world, Governments and insurance companies are often requiring instruments and tools for estimating the possible economic and human losses related to such kind of natural hazard.

Several sets of empirical fragility functions have been proposed in literature after past major tsunami events (Reese et al. 2009, Suppasri et al. 2013, Foytong and Ruangrassamee 2016, among many others). Empirical fragility functions were developed based on post-tsunami damage surveys and are very helpful for understanding the tsunami induced damage to both structural and non-structural components. However, these fragility functions are strongly related to both the typological building features in damages area and the tsunami itself. Thus, the adoption of such curves for a risk-assessment analysis in different areas and for generic tsunami scenarios can provide misleading results.

Current research is recently moving to the definition of analytical methods able to predict the structural behaviour of buildings subjected to tsunami loading (Petrone et al. 2017, Karafagka et al. 2018, Alam et al. 2018, Del Zoppo et al. 2019) for the definition of analytical fragility functions. However, due to the recent interest on this topic, there is no consensus about the definition of damage states prior the collapse of the building.

In this paper, a brief literature review about the empirical damage states is reported. Then, analytical limit states already presented in literature are discussed and mechanical damage states for both structural and non-structural components are proposed.

Empirical damage states

Empirical fragility functions were built after past major tsunami events mainly based on observed building damage due to the tsunami (often coupled to the damage caused by the earthquake). The observed damage to buildings was then correlated to a tsunami intensity measure, which is commonly assumed as the wave inundation depth due to the simplicity of measure such parameter on inundated buildings.

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Different damage states were used for empirical fragility functions based on qualitative definitions of the observed damage. For instance, after the Indian Ocean Tsunami (2004), fragility functions were developed for the Thailand (Ruangrassamee et al. 2006) and Sri Lanka (Murao and Nakazato 2010) areas. Reese et al. (2011) proposed fragility functions for the South Pacific Tsunami (2009) and Suppasri et al. (2012) developed empirical fragility functions after the Great Est Japan tsunami (2011). A critical review of currently available empirical fragility functions is reported in Charvet et al. (2017).

The tsunami-induced damages to structural members were mainly in the form of high flexural deformations or shear failures for columns, lateral bending of beams, failure of beam-to-column joints and erosion of soil below the foundations. Furthermore, several buildings were completely overturned.

Non-structural components (i.e. masonry infills) mainly exhibited punching out-of-plane failures (see Fig. 1), especially in the absence of openings. Conversely, infilled walls with openings showed minimum damage during the tsunami (Ruangrassamee et al. 2006).

Among the definitions of the empirical damage states, the one proposed by the Ministry of Land, Infrastructure and Transportation of Japan (MLIT) appears the most accurate for reinforced concrete buildings. According to MLIT, six damage states are identified after the Great Est Japan tsunami (2011), ranging from minor damage to completely washed away, as reported in Table 1. Even though the qualitative nature of this classification, it is very helpful for understanding the progression of damage. It is observed that the damage states DS1-3 are mainly related to non-structural components. Conversely, damage states DS4-5 are related to structural members and damage state DS6 involves the global overturning mechanism of the building.

Figure 1. Punching failure of infill wall (Ruangrassamee et al. 2006).

Empirical damage state	**Classification**	**Description**
MLIT_DS1	Minor damage	No significant structural or non-structural damage, minor flooding
MLIT_DS2	Moderate damage	Slight damage to non-structural components
MLIT_DS3	Major damage	Heavy damage to some infill walls but no damages in columns
MLIT_DS4	Complete damage	Heavy damages to several infill walls and some columns
MLIT_DS5	Collapsed	Destructive damage to infill walls (more than half of wall density) and several columns (bend or destroyed)
MLIT_DS6	Washed away	Washed away, only foundation remained, total overturned

Table 1. Empirical damage state (MLIT, Suppasri et al. 2012).

Analytical damage states

For the definition of analytical fragility functions, specific structural models should be developed for predicting the behaviour of both structural and non-structural members, based on the tsunami-induced observed damages. Only few researches proposed analytical models for the definition of damage states prior the collapse.

In Macabuag and Rossetto (2014), the MLIT damage states have been associated to analytical damage states. In particular: the MLIT_DS1-2 were neglected, MLIT_DS3 was associated to the first yielding of longitudinal rebars (DS1), MLIT_DS4 was associated to the concrete cover spalling (DS2), MLIT_DS5 to the crushing of concrete core (DS3) and MLIT_DS6 to the achievement of a numerical instability of the model (DS4). All these mechanisms were related to the exceeding of a certain threshold value, mainly consisting in material strains as reported in Table 2. The failure of breakaway infill panels was not taken into account in the model. In successive studies (Petrone et al. 2017), only the collapse condition was considered as damage state, due to the development of flexural mechanism or to the shear failure of columns.

Conversely, Karafagka et al. (2018) proposed a progressive damage state classification based on that developed by Crowley et al. (2004) for damages caused by earthquakes. In this case, four damage state are identified for structural members: none to slight, corresponding to the development of first cracks; moderate, corresponding to the cover spalling; extensive, corresponding to large cracks and bucking of rebars; complete, corresponding to the collapse. Also in this case, all damage states are associated to threshold values on material (longitudinal steel in this case) strains. Different threshold values were identified for bare or infilled RC frames, as reported in Table 2. However, the role of masonry infills was only investigated in the in-plane performance of the frame, neglecting the out-of-plane failure of infills.

Analytical damage state	**Macabuag and Rossetto (2014)**	**Karafagka et al. (2018) Bare frame**	**Karafagka et al. (2018) Infilled frame**
DS1	$\varepsilon_s > \varepsilon_{sy}$	$\varepsilon_s > \varepsilon_{sy}$	$\varepsilon_s > 0.0007$
DS2	$\varepsilon_c > -0.0025$	$\varepsilon_s > 0.0125$	$\varepsilon_s > 0.002$
DS3	$\varepsilon_c > -0.0031$	$\varepsilon_s > 0.025$	$\varepsilon_s > 0.010$
DS4	Numerical instability	$\varepsilon_s > 0.045$	$\varepsilon_s > 0.020$

Table 2. Analytical damage states developed for case-study buildings from literature.

Proposed damage states

The analysis of the damage occurred after tsunami events attested the important role of breakaway infills in the overall damage of buildings. Indeed, the external infills orthogonal to the tsunami direction are mainly responsible of transferring the tsunami wave pressure to the structural members. Thus, their failure would strongly reduce the load acting on the structure.

Furthermore, the analysis of reconstruction costs after seismic events (De Martino et al. 2017) confirmed that the damage to non-structural components strongly affects the total reconstruction costs. For these reasons, the damage of non-structural members should be considered in the definition of analytical damage states and related fragility functions.

In the following, six analytical damage states are proposed based on the damage classification provided by the MLIT and accounting for the behaviour of infill walls orthogonal to the tsunami direction, as reported in Table 3. In particular, two DS are identified for non-structural members, three fro the upper structure and one for the overall building. The in-plane damage of partitions is herein neglected, because of the assumption that the out-of-plane failure of external infills at a certain storey coincides with the failure of all the internal partitions at same storey.

The proposed ns_DS1-2 are related to the damage of non-structural components, from a light damage to the collapse of external infills. Damage states s_DS1-3 represent the damage to structural members (i.e. columns, beams) due to the hydrostatic, hydrodynamic and uplift loads acting on the upper structure, up to the achievement of flexural failure mechanism (i.e. usually a soft storey mechanism). The damage induced by the shear failure of columns was considered in a specific damage state (s_DSshear), since it is not related to the damage progression induced by the flexural deformation. Whereas damage state f_DS1 accounts for the global overturning mechanism due to buoyancy and uplift forces that involve the soil-foundation interaction.

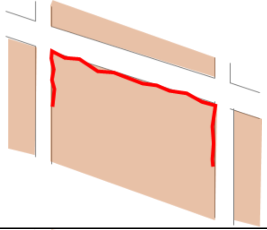
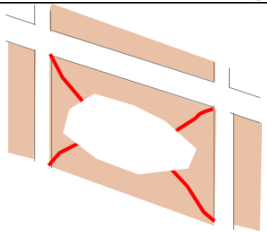
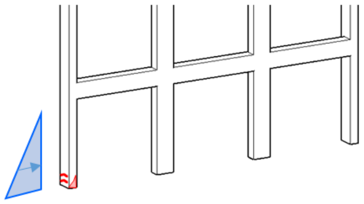
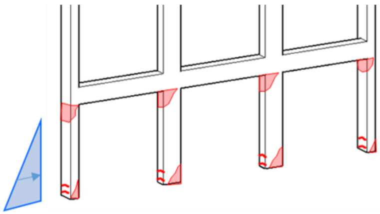
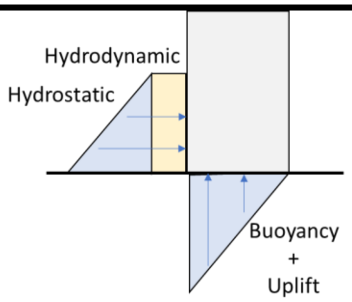
Member	**Proposed damage state**	**Description**	**Mechanical model**
NON-STRUCTURAL MEMBERS	ns_DS1	Light damage to external infills orthogonal to the tsunami direction	
	ns_DS2	Collapse of external infills orthogonal to the tsunami direction	
UPPER STRUCTURE	s_DS1	Light damage to structural members (one-half of yielding deformation, $\varepsilon_s > 0.5\varepsilon_{sy}$)	
	s_DS2	Moderate damage to structural members (first yielding, $\varepsilon_s > \varepsilon_{sy}$)	
	s_DSshear	Columns shear failure	
	s_DS3	Global collapse (soft storey mechanism)	
SOIL-FOUNDATION	f_DS1	Global overturning	

Table 3. Proposed analytical damage states for non-structural members, upper structure and foundation.

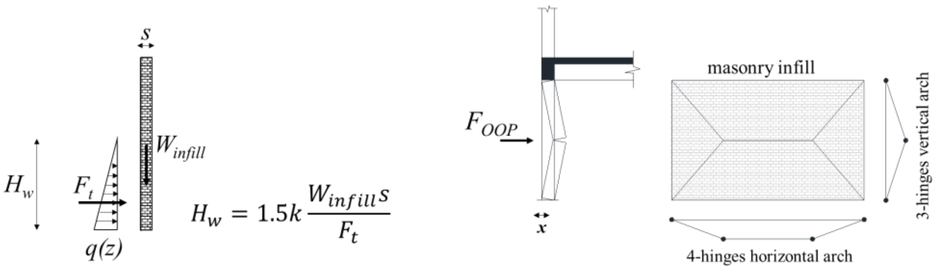
It should be noted that the evaluation of the proposed damage states requires the definition of specific analytical or numerical models for the infills, for the RC frame and for the overall soil-foundation-structure system.

The current research about the behaviour of infills masonry panels subjected to tsunami loading is quite lacking. In the absence of refined models, the ns_DS1 damage state can be assumed as a light detachment of the external infill from the surrounding frame, calculated with basic overturning equilibrium equations, as depicted in Fig. 2a. Conversely, based on the damage pattern shown in Fig. 1, the damage state ns_DS2 can be simulated with an arch mechanism, as showed in Fig. 2b. Simple equation can be derived from the virtual works principle for estimating the load that activates the mechanism. Further research is needed for evaluating the damage mechanism of such non-structural members under tsunami induced loads. Furthermore, the role of the openings should also be investigated with numerical or experimental simulations.

Conversely, currently available models based on tsunami pushover (Petrone et al. 2017, Karafagka et al. 2018, Del Zoppo et al. 2019) can be adopted for evaluating the damage states related to structural members (i.e. s_DS1-3). However, proper modifications can be adopted in those methods for considering the failure of external infills that changes the load distribution for the entire structure. The threshold values reported in Table 1 can also be adopted for the definition of such damage states in numerical models. However, a proper modelling of the members shear capacity is also required.

Regarding the f_DS1 damage state, specific considerations should be done about the foundation system (i.e. piles or superficial foundations), which is mainly responsible of the resisting mechanism, and on the soil mechanical properties. More research is needed on this topic for the proper definition of such failure mechanism.

The herein proposed analytical damage states do not account for the effects of debris impact or impulsive forces.



(a) (b)

Figure 2. Mechanical models for ns_DS1 (a) and ns_DS2 (b).

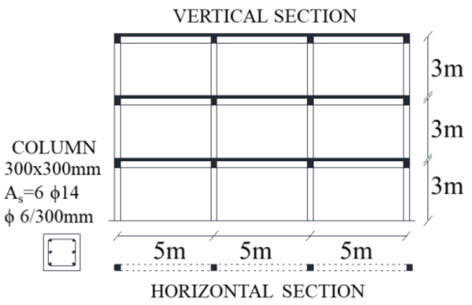
Applicative example

The achievement of the proposed DSs was calculated for a sample plane RC frame representative of existing buildings in Mediterranean area subjected to the lateral pressure induced by a tsunami flow. The tsunami lateral pressure was estimated according to the MLIT guidelines, which assume a hydrostatic load distribution amplified by 1.5 for accounting for the hydrodynamic effects. This method, due to its simple format, overestimates the tsunami load but it is also more suitable for large-scale loss-assessment analysis.

The 3-storey and 3-bay RC frame (Fig. 3a) herein analysed has been designed for gravity loads only, according to the allowable stress method. The inter-storey height was 3m and the bay span was 5m. The columns had a square cross-section, 300x300mm, with a longitudinal reinforcement of 6 ϕ14 and transverse reinforcement made by ϕ6 spaced at 300mm. A medium-quality concrete with compressive strength 20 MPa was assumed. The yielding stress of steel rebars was 380 MPa. For the external masonry infills, a thickness of 25cm and a unit weight of 8 kN/m^3 were hypnotized. The damage states for non-structural members were evaluated as reported in Fig.2. Conversely, DSs for structural members were calculated using the Variable Height Pushover Analysis for buildings with breakaway infills described in Del Zoppo et al. 2019.

The tsunami inundation depths corresponding to the achievement of each proposed DS in Table 2 are reported in Fig. 3b. The overturning mechanism was not considered in the analysis, due to the lack of validated models. The analysis results showed that the damage to the external masonry infills started from an inundation depth of 0.5m up to the collapse for an inundation depth of 1.5m. Conversely, the structural damage due to flexure started at an inundation depth of 1.7m and the structural collapse (i.e. soft-storey mechanism at the first storey) happened for an inundation depth of 3.2m. However, it should be noted that the first shear failure of columns was recorded at an inundation depth of 1m, which is even before the collapse of the external infills.

Indeed at this condition, the high load transferred by the infills to the adjacent columns led the development of high shear stresses. In the case of existing RC columns, characterized by a poor shear capacity, this high load can induce a premature shear failure of columns before the development of flexural mechanisms.



(a)

Analytical damage state	Inundation depth [m]
ns_DS1	0.5
ns_DS2	1.5
s_DS1	1.7
s_DS2	2.8
s-DSshear	1.0
s_DS3	3.2

(b)

Figure 3. RC frame details (a) and inundation depths for each DS (b).

Conclusions

The definition of analytical damage states is of paramount importance for the development of analytical fragility functions to be used in a risk-assessment framework. The empirical fragility functions were very helpful in the definition of the tsunami-induced damages to both structural and non-structural components.

Currently available analytical damage state classifications are mainly related to the structural members and are based on the exceedance of certain engineered parameters threshold values. However, these classifications do not account for the non-structural components and for the global failure of the building due to overturning.

Six analytical damage states are proposed, based on the empirical damage classification provided by MLIT and accounting for the damage to non-structural members. Simplified mechanical models are also proposed for evaluating the damage of non-structural components.

An applicative example was reported for a 3-storey case-study RC frame typical of existing buildings and the progression of damages was showed, underlining the risk of columns shear failure before the development of flexural mechanism.

This study also underlined the need of more specific research on the behaviour of non-structural components under tsunami actions, considering also the role of openings, and on the definition of proper models for the overturning mechanism.

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